Spin effects in high energy diffractive reactions.

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Abstract

It is shown that single and double spin asymmetries in polarized diffractive $Q\bar{Q}$ production depend strongly on the spin structure of the quark-pomeron vertex. They can be studied in future spin experiments at HERA.

Experimental observations of the diffractive production of high p_t jets in hadron-hadron and lepton-proton reactions [1, 2] have stimulated the study of pomeron properties. Diffractive reactions with high p_t jets can be interpreted in terms of the partonic structure of a pomeron [3]. It has been shown that the observed effects can be predominated by the quark structure of a pomeron [4, 5].

The pomeron is a vacuum t-channel exchange that contributes to high-energy diffractive reactions. The nonperturbative two-gluon exchange model [6, 7] and the BFKL model [8] of a pomeron lead to the mainly imaginary scattering amplitude that can be written as a product of pomeron vertices $V_{\mu}^{hh\mathbb{P}}$ and some function $\mathbb{P}$ determined by the pomeron. As a result, the pomeron contribution to the quark-proton amplitude looks as follows

$$T(s,t) = i\mathbb{P}(s,t)\, V^{\mu}_{qq\mathbb{P}} \otimes V_{\mu}^{pp\mathbb{P}}. \tag{1}$$

In models [7, 8] the pomeron couplings have a simple matrix structure:

$$V^{\mu}_{hh\mathbb{P}} = \beta_{hh\mathbb{P}}\, \gamma^{\mu}, \tag{2}$$

which reflects the well-known approximation that the spinless quark-pomeron coupling is like a $C = +1$ isoscalar photon vertex. In this case the spin-flip effects are very small.

However, the spin structure of quark-pomeron coupling may be not so simple. The perturbative calculations [9] show the quark-pomeron vertex complicated in form :

$$V^{\mu}_{qq\mathbb{P}}(k,r) = \gamma_{\mu} u_0 + 2mk_{\mu} u_1 + 2k_{\mu} \not{k} u_2 + iu_3 \epsilon^{\mu\alpha\beta\rho} k_{\alpha} r_{\beta} \gamma_{\rho} \gamma_5 + imu_4 \sigma^{\mu\alpha} r_{\alpha}. \tag{3}$$

Here k is a quark momentum, r is a momentum transfer. The structure of the quark-pomeron vertex function (3) is drastically different from the standard pomeron coupling (2). Really, the terms $u_1(r) - u_4(r)$ lead to the spin-flip in the quark-pomeron vertex in contrast to the term proportional to $u_0(r)$. The

functions $u_1(r) \div u_4(r)$ at large r^2 are not very small [10]. Note that the phenomenological vertex $V^{\mu}_{qq\mathbb{P}}$ with u_0 and u_1 terms has been proposed in [11].

The proton-pomeron vertex has been found in some models (see [12] e.g.):

$$V^{\mu}_{pp\mathbb{P}}(p,r) = mp_{\mu}A(r) + \gamma_{\mu}B(r), \tag{4}$$

which is similar in form to that from Ref. [11]. The quantity A in (4) determines the transverse polarization and B contributes to the longitudinal asymmetry.

Thus, the pomeron vertices have a complicated spin structure. This should modify different spin asymmetries in high energy diffractive reactions that can be measured, for example, in future spin experiments at HERA.

We would like to show that one of the simplest way to test the quark-pomeron vertex is to study the $Q\bar{Q}$ production in diffractive reactions.

In this report we shall discuss the longitudinal double spin asymmetries in polarized $p \uparrow p \uparrow \to p + Q\bar{Q} + X$ and $l \uparrow p \uparrow \to l + p + Q\bar{Q}$ diffractive reactions, single transverse spin asymmetry in similar reactions. Such experiments will be possible in the future HERA-N project and at HERA with a polarized proton beam.

Let us analyse the $Q\bar{Q}$ production in diffractive pp scattering. We shall investigate graphs where the pomeron with a nonzero momentum transfer interacts with one quark in the loop. The integration over all the $Q\bar{Q}$ phase space will be performed. It has been shown in our previous estimations [13] that A_{ll} asymmetry in this case can reach $10 \div 12\%$.

The standard kinematical variables look as follows

$$s = (p_i + p)^2,\ t = r^2 = (p - p')^2,\ x_p = \frac{p_i(p - p')}{p_i p}. \tag{5}$$

Here p_i and p are initial proton momenta, p' is a momentum of a recoil hadron, r is a momentum transfer at the pomeron vertex and x_p is a part of the momentum p carried off by the pomeron. The investigated process is important at small x_p that lead to a small invariant mass in the $Q\bar{Q}$ system $M_x^2 \sim \bar{x}_p s$. The diagram with a triple pomeron vertex must be considered for large M_x^2. Then we shall see more than two high p_t jets.

We shall study the region where $|t|$ is a few GeV^2 and $x_p \sim 0.1 \div 0.2$. For this $|t|$ the perturbative QCD can be used for calculating the spin structure of the quark-pomeron vertex.

We shall investigate the longitudinal double spin asymmetry determined by the relation

$$A_{ll} = \frac{\Delta\sigma}{\sigma} = \frac{\sigma(\rightleftarrows) - \sigma(\rightrightarrows)}{\sigma(\rightrightarrows) + \sigma(\rightleftarrows)}. \tag{6}$$

For the spin-average and longitudinal polarization of the proton beam the B term in (4) is predominant. As a result, the longitudinal double spin asymmetry does not depend on the pomeron-proton vertex structure.

We find that $\sigma \propto 1/x_p^2$ at small x_p. This behaviour is associated usually with the pomeron flux factor for $\alpha_{I\!P}(0) = 1$. However, $\Delta\sigma$ is proportional to $\epsilon^{\mu\nu\alpha\beta} r_\beta ... \propto x_p p$. Thus, additional x_p appears and we find that $\Delta\sigma \propto 1/x_p$ at small x_p.

In calculations of the corresponding integrals, the off-mass-shell behaviour of the pomeron structure functions u_i has been considered. The simple form of the $u_0(r)$ function

$$u_0(r) = \frac{\mu_0^2}{\mu_0^2 + |t|}, \quad r^2 = |t|,$$

was used with $\mu_0 \sim 1Gev$ introduced in [14]. The functions $u_1(r) \div u_4(r)$ at $|t| > 1GeV^2$ were calculated in perturbative QCD [10].

The main contribution to $\Delta\sigma$ is proportional to the first moment of Δg

$$\Delta g = \int_0^1 dy \Delta g(y), \tag{7}$$

which is unknown up to now. In explanation of the proton spin [15] a large magnitude of $\Delta g \sim 3$ is used, as a rule.

We use a simple form of the gluon structure function which contributes to σ:

$$g(y) = \frac{R}{y}(1-y)^5, \quad R = 3.$$

The resulting asymmetry is proportional to the ratio

$$C_g = \frac{\Delta g}{R}. \tag{8}$$

For $\Delta g \sim 3$ we have $C_g \sim 1$. This magnitude will be used in what follows. However, it was mentioned in [16] that the magnitude $\Delta g \sim 1$ is more preferable now. In this case C_g will be about .3 and the results will decrease by factor 3.

For a standard form of the pomeron vertex (2) we find [17]

$$A_{ll} = \frac{-2x_p(\ln \frac{|t|}{M_Q^2} - 3)}{\ln \frac{|t|}{M_Q^2}(2\ln \frac{s x_p}{4|t|} + \ln \frac{|t|}{M_Q^2})} C_g. \tag{9}$$

For the pomeron vertex (3) the axial-like term $V^\mu(k,r) \propto u_3(r)\epsilon^{\mu\alpha\beta\rho} k_\alpha q_\beta \gamma_\rho \gamma_5$ is extremely important in asymmetry. The formula for asymmetry is more complicated in this case.

Our predictions for A_{ll} asymmetry at $\sqrt{s} = 40GeV$ (HERA-N energy) and $x_p = 0.2$ for a standard quark-pomeron vertex (2) and spin-dependent quark-pomeron vertex (3) are shown in Fig.1 for light quarks and in Fig.2 for a heavy (C) quark. It is easy to see that the obtained asymmetry strongly depends on the structure of the quark-pomeron vertex. For a spin-dependent quark-pomeron vertex A_{ll} asymmetry is smaller by factor 2 because σ in (6) is larger in this case due to the contribution of other u_i structures.

As it was mentioned above, the asymmetry in pp polarized diffractive reactions depends on the unknown the spin–gluon structure function Δg of the proton. To obtain more explicit results, let us study the $Q\bar{Q}$ diffractive production in a lepton-proton reaction at small x_p.

The standard set of kinematical variables looks as follows [2]

$$s = (p_l + p)^2, \;\; Q^2 = -q^2, \; t = (p - p')^2$$
$$y = \frac{pq}{p_l p}, \; x = \frac{Q^2}{2pq}, \; \beta = \frac{Q^2}{2q(p - p')}, \; x_p = \frac{q(p - p')}{qp}, \tag{10}$$

where p_l, p'_l and p, p' are initial and final lepton and proton momenta, respectively, $q = p_l - p'_l$.

The asymmetry is determined by formula (6). The main contributions to A_{ll} asymmetry in the discussed region are determined by the u_0 and u_3 structures in (3). The formulae for σ and $\Delta\sigma$ for different forms of the pomeron vertex can be found in [18]. Note that $\Delta\sigma$ is proportional to Q^2. As a result, the asymmetry must increase with Q^2.

Our predictions for A_{ll} asymmetry for the maximal HERA energy $\sqrt{s} = 300GeV$ estimated ¿from perturbative vertex functions for $y = 0.5$ and $x_p = 0.2$ for a standard quark–pomeron vertex and a spin-dependent quark–pomeron vertex are shown in Fig.3. In this figure one can see the Q^2 dependence of A_{ll} for fixed $|t| = 3GeV^2$. The obtained asymmetry is not small and strongly depends on the spin structure of the quark-pomeron vertex. Asymmetry decreases with growing $|t|$ and increases with growing Q^2.

The single-spin asymmetry differs from the longitudinal asymmetry. It is determined by the relation

$$A_{\perp} = \frac{\sigma(^{\uparrow}) - \sigma(^{\downarrow})}{\sigma(^{\uparrow}) + \sigma(^{\downarrow})} = \frac{\Delta\sigma}{\sigma} \propto \frac{\Im(f_+^* f_-)}{|f_+|^2 + |f_-|^2}, \tag{11}$$

where f_+ and f_- are spin-non-flip and spin-flip amplitudes, respectively. So, the single–spin asymmetry appears if both f_+ and f_- are nonzero and there is a phase shift between these amplitudes.

For elastic reactions this asymmetry can be predominated by the so–called "soft pomeron" that includes the rescatterings effects. For this pomeron the

amplitudes f_+ and f_- can possess a phase shift. As a result the transverse hadron asymmetry determined by the pomeron exchange

$$A_\perp^h \simeq \frac{2m\sqrt{|t|}\Im(AB^*)}{|B|^2}. \tag{12}$$

appears. Here amplitudes A and B determined in (4) are related with the proton wave function and can be calculated by model approaches (see [12] e.g.). The model [12] predicts that polarization at $|t| \simeq 1GeV^2$ can be about $10 \div 15\%$.

Let us investigate the single transverse spin asymmetry in $p \uparrow p \to p + Q\bar{Q} + X$ reaction. Standard kinematical variables were determined in (5). In what follows we shall calculate the distributions of jets over $p_\perp^2$.

The cross sections σ and $\Delta\sigma$ can be written in the form

$$\frac{d\sigma(\Delta\sigma)}{dx_p dt dp_\perp^2} = \{1, A_\perp^h\} \frac{\beta^4 |F_p(t)|^2 \alpha_s}{128\pi s x_p^2} \int_{4p_\perp^2/sx_p}^1 \frac{dy g(y)}{\sqrt{1 - 4p_\perp^2/syx_p}} \frac{N^{\sigma(\Delta\sigma)}(x_p, p_\perp^2, u_i, |t|)}{(p_\perp^2 + M_Q^2)^2}. \tag{13}$$

Here g is the gluon structure function of the proton, $p_\perp$ is a transverse momentum of jets, M_Q is a quark mass, $N^{\sigma(\Delta\sigma)}$ is a trace over the quark loop, β is a pomeron coupling constant, F_p is a pomeron-proton form factor. In (13) the coefficient equal to unity appears in σ and the transverse hadron asymmetry $A_\perp^h$ at the pomeron-proton vertex (12) appears in $\Delta\sigma$.

In the diffractive–jet production investigated here the main contribution is determined by the region where the quarks in the loop are not far of the mass shell. So, we can assume that the asymmetry factor in (13) can be determined by the soft pomeron and it coincides with the elastic transverse hadron asymmetry (12). In our further estimations we use magnitude $A_\perp^h = 0.1$. New model calculations for the pomeron-proton coupling (4) are very important. For this purpose, the diquark model [19] should be useful.

Both σ and $\Delta\sigma$ have a similar dependence at small x_p

$$\sigma(\Delta\sigma) \propto \frac{1}{x_p^2}$$

This property of (13) allows one to study asymmetry at small x_p where the pomeron exchange is predominated because of a high energy in the quark-pomeron system.

In calculations we use the magnitude $\beta = 2GeV^{-1}$ [14] and the exponential form of the form factor

$$|F_p(t)|^2 = e^{bt} \quad \text{with} \quad b = 5GeV^2.$$

Our predictions for asymmetry $A_\perp$ at $\sqrt{s} = 40GeV$, $x_p = 0.05$ and $|t| = 1GeV^2$ for a standard quark-pomeron vertex (2) and a spin-dependent quark-pomeron vertex (3) are shown in Fig.4 for light-quark jets. It was found that the main contributions to σ and $\Delta\sigma$ are determined by the u_0 and u_3 terms in (3).

It is easy to see that the shape of asymmetry is different for standard and spin-dependent pomeron vertices. In the first case it is approximately constant in the second it depends on $p_\perp^2$. So, from this asymmetry the structure of the quark-pomeron vertex can be determined.

We calculate the integrated over $p_\perp^2$ of jet cross sections σ and $\Delta\sigma$, too. The asymmetry obtained from these integrated cross sections does not depend practically on the quark-pomeron vertex structure. It can be written in both the cases in the form

$$A1 = \frac{\int dp_\perp^2 \Delta\sigma}{\int dp_\perp^2 \sigma} = 0.5\ A_\perp^h \tag{14}$$

As a result, the integrated asymmetry (14) can be used for studying of the transverse hadron asymmetry $A_\perp^h$ at the pomeron-proton vertex.

To summarize, we have presented in this report the perturbative QCD analysis of longitudinal double and single transverse spin asymmetries in the diffractive 2-jet production in lp and pp processes. The spin-dependent contributions to the quark-pomeron and hadron-pomeron couplings discussed here modify the calculated spin asymmetries. The obtained asymmetries in the lepton-proton and proton-proton processes have some important properties:

- A_{ll} asymmetry is opposite in sign for light and heavy quarks;
- Asymmetry for open charm production is sufficiently large;
- Relavent asymetry in diffractive J/Ψ production can be large too;
- Asymmetry decreases with energy only logarithmically, $A_{ll} \sim 1/ln(sx_p/(4|t|)$;
- Double spin A_{LL} asymmetry is equal to zero at $x_p = 0$. So it is better to study it at $x_p = 0.1 \div 0.2$. Asymmetries strongly depend on the structure the of quark-pomeron vertex;
- The distribution over jets $p_\perp^2$ should be more informative in studying the pomeron vertex structure.

The model prediction shows that the A_{ll} and $A_\perp$ asymmetry can be studied and the information about the spin structure of the quark-pomeron vertex can be extracted, for instance, from the future spin experiments at HERA, HERA-N, RHIC.

It should be emphasized that the spin effects obtained here are completely determined at fixed momenta transfer by large-distance contributions in quark (gluon) loops. So, they have a nonperturbative character. The investigation of spin effects in diffractive reactions is an important test of the spin sector of QCD at large distances.

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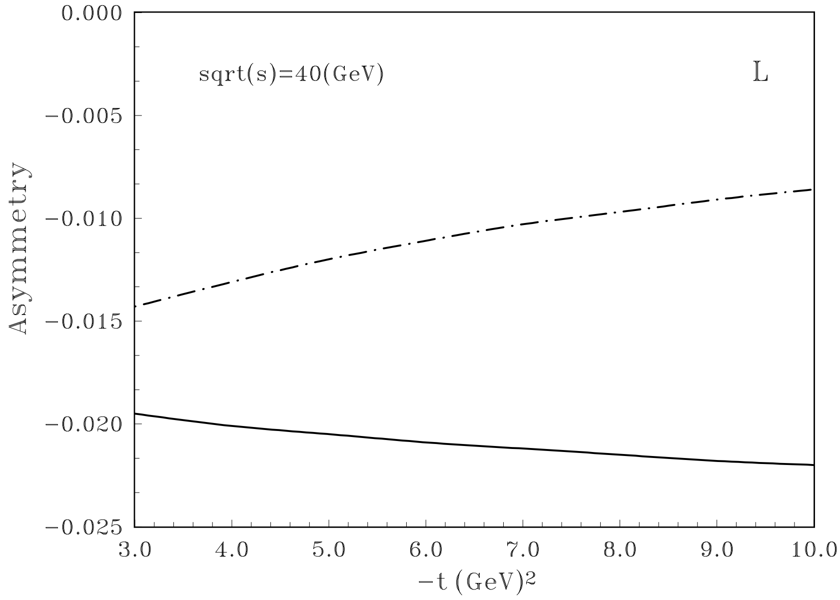

Fig.1 A_{ll} asymmetry of light-quark production. For all figures: solid line -for standard vertex; dot-dashed line -for spin-dependent quark-pomeron vertex.

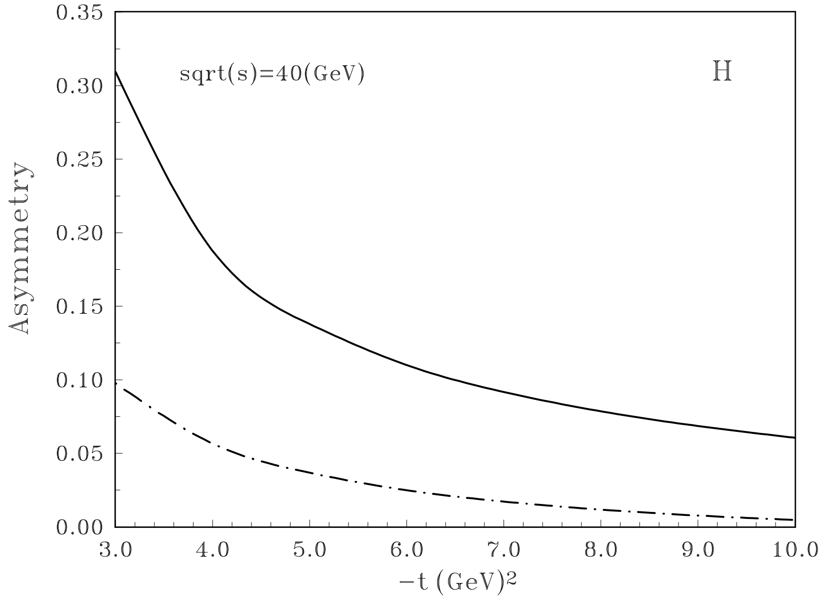

Fig.2: A_{ll} asymmetry of the open charm production.

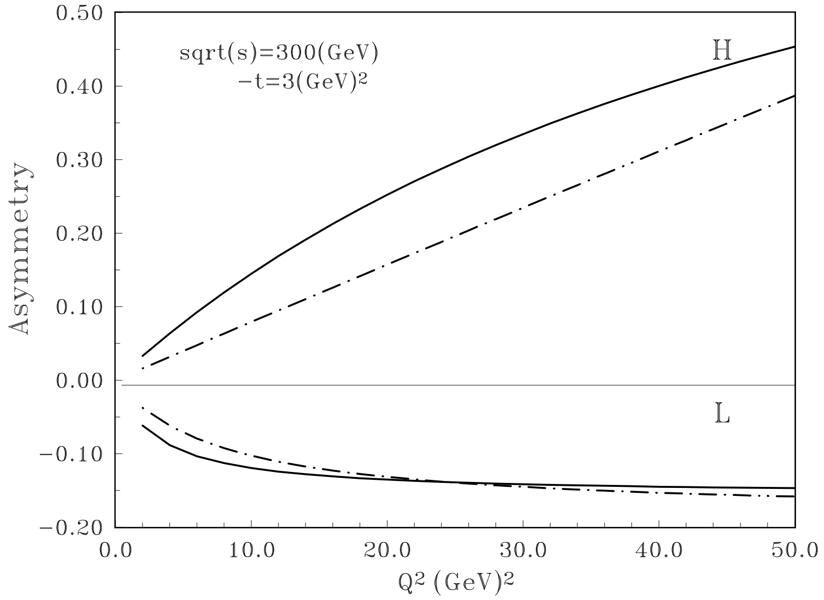

Fig.3 Q^2 dependence of A_{ll} asymmetry of the light and heavy (C) quark production at fixed $|t| = 3GeV^2$.

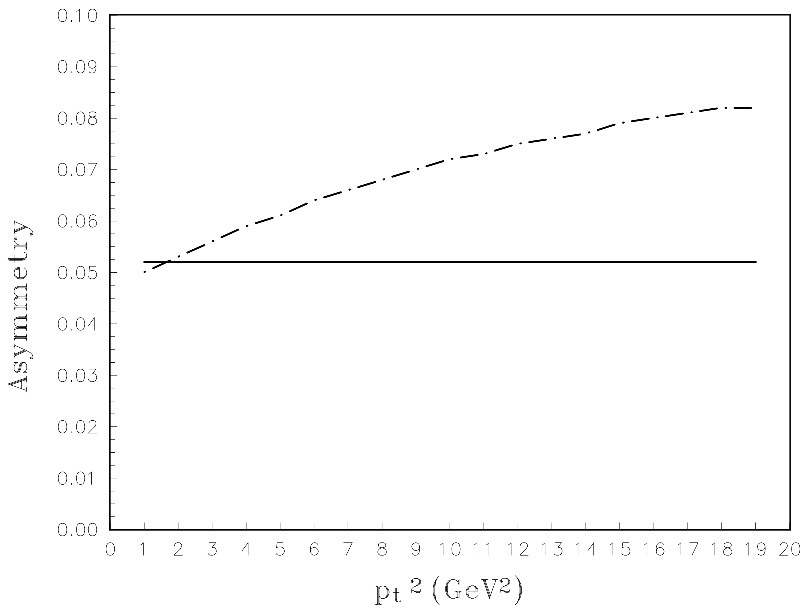

Fig.4: The distribution of $A_\perp$ asymmetry over $p_\perp^2$ of jets of the light quarks production.